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TWO-POINT SCALAR TIME-SERIES MEASUREMENTS IN TURBULENT PARTIALLLY PREMIXED FLAMES

Principal Investigators: Galen B. King, Normand M. Laurendeau and Michael W. Renfro

School of Mechanical Engineering, Purdue University, West Lafayette, IN 47907-2088
Department of Mechanical Engineering, University of Connecticut, Storrs, CT 06269-3139

SUMMARY/OVERVIEW

A two-point method has recently been demonstrated based on picosecond time-resolved laser-induced fluorescence (PITLIF). This technique is capable of simultaneously monitoring OH time series at two locations, hence allowing the characterization of spatial structures in turbulent flames in addition to their temporal behavior. Several refinements have been made to improve upon the previous one-point instrument. Using a specially designed collection-lens system, off-axis optical aberrations have been effectively minimized in the probe volume. Furthermore, additional electronics has been installed which permit absolute species concentration measurements. As a preliminary study, two-point OH time-series measurements were taken in three standard turbulent non-premixed flames (H3, DLR_A and DLR_B)[1]. Two-point statistics, including space-time correlations, spatial autocorrelation functions and integral length scales were computed to help elucidate the flame structure and turbulence-chemistry interactions.

TECHNICAL DISCUSSION

Understanding complex physical and chemical processes in turbulent combustion requires temporally and spatially resolved measurement techniques. Non-premixed jet flames have been extensively studied because of their relative simplicity and well-defined flow field. Measurements of minor species concentrations in turbulent flames are important owing to their significance to chemical reactions and pollutant formation. Hydroxyl, in particular, is a good flame marker, whose fluctuations reveal important interactions between fluid mixing and chemical reactions.

Time-series measurements of important scalars, such as temperature[2] and concentrations of OH[3] and CH[4] have been demonstrated using high repetition-rate, laser-based techniques. These measurements provide spectral characteristics and relevant time scales for scalars; however, as pointwise measurements, they give no information on spatial structures. To circumvent this limitation, simultaneous multipoint or even 1D or 2D time-series measurements are required. Examples of this endeavor include multipoint OH chemiluminescence measurements[5], two-point temperature measurements[6] and high repetition-rate planar laser-

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[1] TNF workshop, http://www.ca.sandia.gov/TNF

[2] R.W. Dibble, R.E. Hollenbach, Eighteenth Symposium (International) on Combustion, 1981, p. 1489.

[3] M.W. Renfro, W.A. Guttenfelder, G.B. King, N.M. Laurendeau, Combust. Flame 123 (2000) 389.

[4] M.W. Renfro, G.B. King, N.M. Laurendeau, Combust. Flame 122 (2000) 139.

[5] J. Kojima, Y. Ikeda, T. Nakajima, Meas. Sci. Technol. 14 (2003) 1714.

[6] G. H. Wang, N. T. Clemens, P. L. Varghese, Proc. Combust. Inst. 30 (2005) 691.

induced fluorescence (PLIF)[7]. For minor species, two-point PITLIF was previously developed, which provided quantitative concentration measurements of radical species at relevant turbulent temporal and spatial scales[8,9].

Modifications have been made to improve upon the earlier version of the two-point PITLIF system. Optical aberrations were found to have significant effects on our previous two-point statistics[Error! Bookmark not defined.]. In particular, aberrations occurred when either probe volume deviated from the optical axis of the detection system. Furthermore, at large displacement distances, partial overlap arose between images of the two probe volumes. This overlap created artificial coherence between signals from the two probe volumes, which was exhibited as a secondary peak in the spatial autocorrelation function, as depicted in Fig. 1.

Fig. 1. Spatial autocorrelation function of H3 flame taken at the location of peak [OH] at x/D=20, using both the old and new two-point optical systems.

To address this problem, we designed a new lens system via ZEMAX software, which now produces an aberration-limited blur-spot of less than 130 μm at object positions up to 6 mm away from the optical axis. As shown in Fig. 2, the current optical system is composed of one custom-made aspherical lens (L1), a 10-cm diameter UV beamsplitter (BS) and two pairs of plano-convex and meniscus lenses (L2 and L3; L4 and L5). The new setup has a magnification ratio of 1.19 and a working f# of 2.8. Each probe volume is $485{\times}485{\times}210$ μm^3, which is determined by the diameter of the laser beam and the entrance slit width of the monochromators. PITLIF utilizes the principle of triple-bin integration[10] which can correct for the effect of electronic quenching on-the-fly. The insertion of four additional multichannel scalers allows for absolute species concentration measurements at both probe volumes.
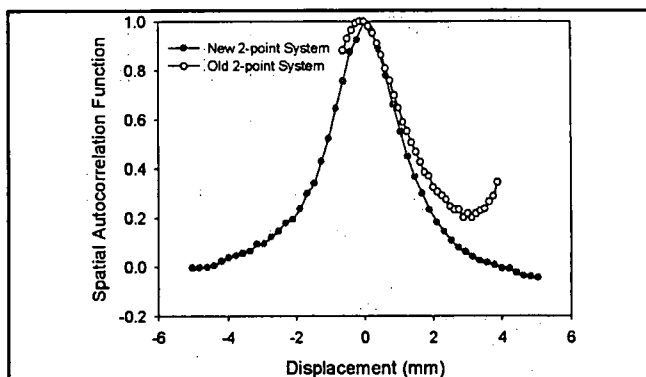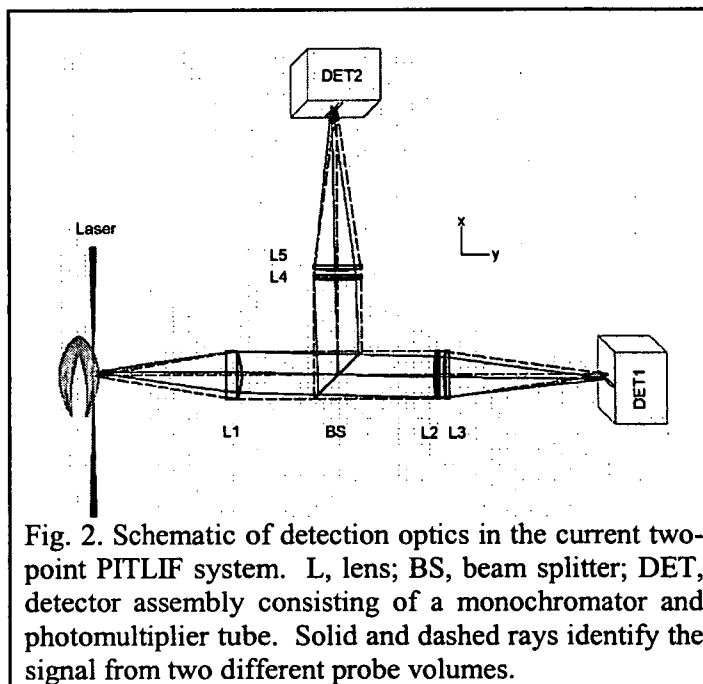

Fig. 2. Schematic of detection optics in the current two-point PITLIF system. L, lens; BS, beam splitter; DET, detector assembly consisting of a monochromator and photomultiplier tube. Solid and dashed rays identify the signal from two different probe volumes.

To demonstrate the effectiveness of this revised setup, two-point PITLIF data were taken at the same position (peak [OH] at x/D=20) within the same flame used by Zhang et al[9]. The derived spatial autocorrelation function shown in Fig.1 displays an approximately exponential decay without a secondary peak, as expected from the typical statistics of a turbulent field.

[7] J. Hult, U. Meier, W. Meier, A. Harvey, C.F. Kaminski, Proc. Combust. Inst. 30 (2005) 701.

[8] J. Zhang, K.K. Venkatesan, G.B. King, N.M. Laurendeau, M.W. Renfro, Proceedings of the 2005 Joint U.S. Sections Meeting, The Combustion Institute, Philadelphia, PA, 2005.

[9] J. Zhang, K.K. Venkatesan, G.B. King, N.M. Laurendeau, M.W. Renfro, Opt. Lett. 30 (2005) 3144.

[10] S.D. Pack, M.W. Renfro, G.B. King, N.M. Laurendeau, Opt. Lett. 23 (1998), 1215.

For this study, three non-premixed flames (H3, DLR_A and DLR_B) were investigated chosen from the TNF workshop[1]. Two-point OH measurements were taken at locations corresponding to the mean peak [OH] as well as positions along the jet centerline, with x/D ranging from 10.00 to 53.25, where x/D=35 and x/D=53.25 correspond to the respective flame tips of the H3 and DLR_A flames. The mean OH concentrations were compared with the available data from the TNF database[1] (the detailed comparison can be found in Zhang et al[11]). The measurements agree quite closely except at two locations: jet centerline at x/D=50 in DLR_A and peak [OH] at x/D=20 in DLR_B. This discrepancy is likely due to deviations in position between the two measurements and increased uncertainty at the jet centerline owing to the small signal-to-background ratio.

Given two simultaneous [OH] time series, a number of two-point statistics can be evaluated, including the space-time correlation, spatial autocorrelation function and integral length scale. The normalized space-time correlation is defined as [12]

$$f_{st}(\Delta r, \Delta t) = \frac{\langle OH'(r,t) OH'(r+\Delta r, t+\Delta t) \rangle}{\left[\langle OH'(r,t)^2 \rangle \langle OH'(r+\Delta r, t+\Delta t)^2 \rangle \right]^{1/2}},$$

where $OH'(r,t)$ is the fluctuating component of hydroxyl concentration at radial location r and time t, while Δr and Δt are the displacement between the two probe volumes and the lag time, respectively. Figure 3 displays the calculated space-time correlation at two peak [OH] locations in the H3 flame. Notice that positions near the flame tip show a broader peak along the displacement axis, indicating a larger coherence region.

The normalized spatial autocorrelation function is related to the space-time correlation by

$$f_s(\Delta r) = f_{st}(\Delta r, \Delta t = 0).$$

Figure 4 displays spatial autocorrelation functions for the DLR_A flame at peak [OH] locations. The full-width-at-half-maximum (FWHM) of the curve becomes greater farther downstream, which is a manifestation of the broadening coherence region mentioned earlier. In general, the
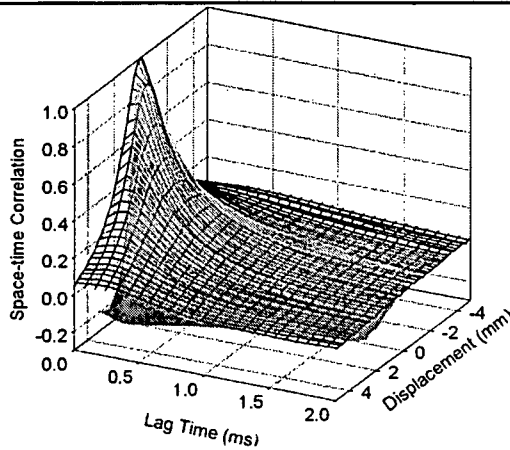

Fig. 3. Space-time correlation at two peak [OH] locations in the H3 flame: (a) x/D=10 (shaded surface); (b) x/D=30 (mesh).
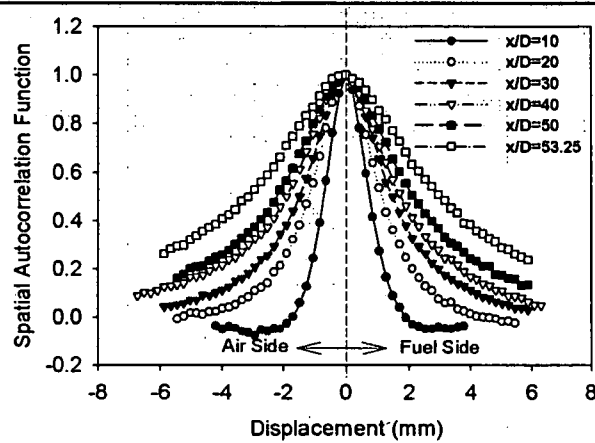
Fig. 4. Normalized spatial autocorrelation functions for the DLR_A flame: (a) at peak [OH] locations.

spatial autocorrelation function is symmetric between the air and fuel sides. Exceptions occur primarily near the nozzle (x/D=10). This abnormality might be explained by the evolution of

[12] M.T. Landahl, E. Mollo-Christensen, Turbulence and Random Processes in Fluid Mechanics, 2nd ed., Cambridge University Press, New York, NY, 1994.

flame structures. In turbulent jet diffusion flames, the reaction zone lower in the flame (e.g. $x/D \leq 5$ for the DLR_A flame) is composed of thin layers located outside the turbulent fuel jet[7,13]. Because of relaminarization, the reaction zone essentially acts as a shield blocking the penetration of fuel vortices; hence, the reaction zone and air side remain laminar. Farther downstream, the flame front becomes more wrinkled as the effect of laminarization diminishes. Therefore, the asymmetry of the spatial autocorrelation function at x/D=10 is probably due to residual laminarization.

The OH integral length scale can be determined by integrating the spatial autocorrelation function over its displacement, Δr, so that

$$l_I = \int f_s(\Delta r) d\Delta r .$$

While the spatial autocorrelation function exhibits asymmetry near the nozzle, the calculated integral length scales are about the same on both sides (Fig. 5). The hydroxyl length scales are well resolved and increase linearly with axial distance at peak [OH] locations (Figs. 5 and 6), consistent with observations of integral length scales for mixture fraction at mean stoichiometric
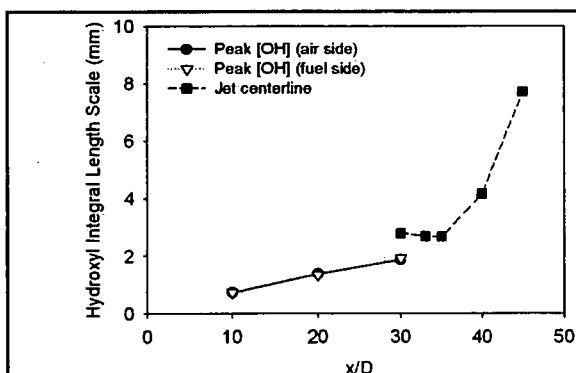

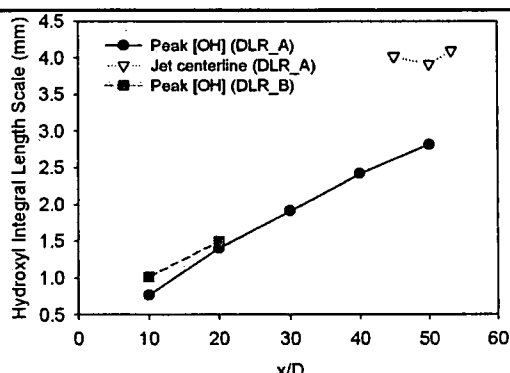Fig. 5. Hydroxyl integral length scales for H3 flame.

Fig. 7. Hydroxyl integral length scales for DLR_A and DLR_B flames.

radii in methane/air jet diffusion flames[14]. This result suggests that OH fluctuations at peak [OH] locations are essentially dominated by flame motions, a confirmation of flamelet theory. The integral length scales are basically constant along the jet centerline below the flame tip, and increase rapidly above the flame tip.

[13] V. Bergmann, W. Meier, D. Wolff, W. Stricker, Appl. Phys. B. 66 (1998) 489.
[14] R.S. Barlow, A.N. Karpetis, Flow Turb. Combust. 72 (2004) 427